

**ORIGIN OF VOLATILE DEPLETION AND THE RELATION OF CHONDRULES AND MATRIX INFERRED FROM TELLURIUM ISOTOPES IN CARBONACEOUS CHONDRITES.** J. L. Hellmann<sup>1</sup>, T. Hopp<sup>1,2</sup>, C. Burkhardt<sup>1</sup> and T. Kleine<sup>1</sup>, <sup>1</sup>University of Münster, Institut für Planetologie, Münster, Germany. <sup>2</sup>Origins Laboratory, Department of the Geophysical Sciences and Enrico Fermi Institute, The University of Chicago, IL, USA. (jan.hellmann@wwu.de)

**Introduction:** Carbonaceous chondrites (CC) are pristine assemblages consisting of refractory inclusions, chondrules, matrix, and metal. As such, they provide fundamental constraints on processes within the solar accretion disk. The distinct CC groups exhibit chemical fractionations relative to the most primitive group, the CI chondrites. These fractionations depend on geochemical affinity and volatility [1,2]. However, in particular the depletion of volatile elements (50% condensation temperature ( $T_c$ ) <1250 K) and how this depletion relates to the formation of chondrules is poorly understood. The degree of volatile depletion is inversely correlated with the amount of matrix, suggesting that the CCs represent mixtures of volatile-rich matrix and volatile-poor chondrules or refractory inclusions [1,2]. More recent versions of this 'two-component model' strengthen the idea that volatile elements derive entirely from CI-like matrix, and that the volatile depletion among the CCs reflects different amounts of matrix [3,4].

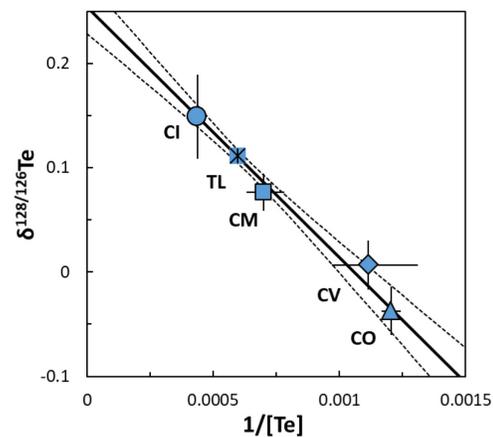
However, other observations are more difficult to reconcile with the two-component model. For instance, some volatile elements exhibit mass-dependent isotope variations among the CC groups, indicating that these volatile elements derive from more than one component [e.g., 5,6]. Moreover, for non-volatile elements chondrules and matrix have complementary chemical and isotopic compositions [7,8], suggesting that both components derive from a common source, and not from two distinct sources.

To better understand the origin of volatile fractionations in CCs, and the role of chondrules and matrix in producing these fractionations, we investigated the mass-dependent Te isotope fractionation among various CC groups. Tellurium is well suited for this task because it is a moderately volatile element (50%  $T_c$  ~700 K), is variably depleted among the CCs, and exhibits isotope fractionation among chondrites [9].

**Samples and analytical methods:** Nineteen carbonaceous chondrites, including two CI, six CM, four CV, two CO chondrites, and the ungrouped chondrite Tagish Lake (TL) were investigated. Sample powders were spiked with a <sup>123</sup>Te-<sup>125</sup>Te double spike, digested in HF-HNO<sub>3</sub>, and Te was purified using a three-stage column chemistry modified after [9,10]. The Te isotope measurements were performed using a Neptune Plus MC-ICPMS at Münster combined with a Cetac

*Aridus II*. Results are reported in  $\delta^{128/126}\text{Te}$  as the permil deviation from the NIST SRM 3156 Te standard.

**Results:** The overall variation in  $\delta^{128/126}\text{Te}$  and Te concentrations among the CCs is ~0.2‰ and ~800 to ~2300 ng/g, respectively. Importantly, samples from a given CC group have indistinguishable  $\delta^{128/126}\text{Te}$  and display a narrow range of Te concentrations. Together with TL, the CC groups define a trend from heavy  $\delta^{128/126}\text{Te}$  and higher Te concentration to lighter  $\delta^{128/126}\text{Te}$  and lower Te concentration (Fig. 1).



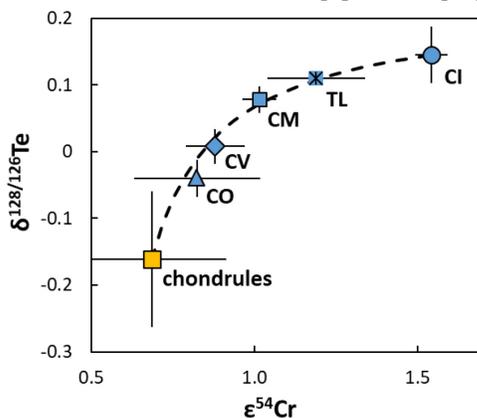
**Fig. 1.**  $\delta^{128/126}\text{Te}$  vs.  $1/[\text{Te}]$  for carbonaceous chondrite groups. Error bars are 2 s.d.

**Discussion:** Samples from a given CC group but of different petrologic type display indistinguishable  $\delta^{128/126}\text{Te}$ , suggesting that their Te isotopic compositions are not affected by parent body processes such as aqueous alteration or thermal metamorphism. We, therefore, interpret the measured  $\delta^{128/126}\text{Te}$  of these samples as the primary signatures of their bulk parent bodies. The CC groups together with TL define a precise linear trend in a plot of  $\delta^{128/126}\text{Te}$  versus  $1/[\text{Te}]$  (Fig. 1), indicating that the Te isotopic and elemental variations reflect mixing between isotopically heavy, volatile-rich and isotopically light, volatile-poor components. The  $\delta^{128/126}\text{Te}$  values and Te concentration also correlate with the fraction of matrix in each CC group, which is highest in CI and lowest in CV and CO chondrites. Combined these observations suggest that the isotopically heavy and volatile-rich end-member is CI-like matrix. This implies that all CCs contain CI-like material, consistent with the two-component mixing model for chondrites [1-4].

The non-matrix component is isotopically light, and given that the different CC groups show distinct

$\delta^{128/126}\text{Te}$  signatures, must have contained some Te. Otherwise, all CC groups would show the same, CI-like  $\delta^{128/126}\text{Te}$ . Consequently, contrary to prior suggestions [1–4], volatile elements in carbonaceous chondrites do not entirely derive from CI-like matrix, but also from the non-matrix component. Nevertheless, for elements with  $T_c$  below  $\sim 750$  K all CC groups display CI chondritic relative abundances, despite different degrees of depletion [3]. These observations can be reconciled if volatile elements in the non-matrix component, despite their overall depletion, are also present in CI-chondritic relative abundances.

The non-matrix component may be represented by chondrules, refractory inclusions, or metal. Metal is not sufficiently variable among the CC groups to account for the differences in  $\delta^{128/126}\text{Te}$ . By contrast, the amount of both refractory inclusions and chondrules correlate with the degree of volatile element depletion, and so both may represent the volatile-poor and isotopically light non-matrix component. This is consistent with the observation that CAIs and chondrules are isotopically light for volatile elements like Zn [5] and Cd [11].



**Fig. 2.**  $\delta^{128/126}\text{Te}$  versus  $\epsilon^{54}\text{Cr}$  for carbonaceous chondrites.  $\delta^{128/126}\text{Te}$  of 'chondrules' inferred from the correlations of  $\delta^{128/126}\text{Te}$  and Te concentration of CC groups with the amount of matrix. Dashed line is a calculated mixing line between CI chondrites and chondrules.

The  $\delta^{128/126}\text{Te}$  values are also correlated with nucleosynthetic  $\epsilon^{54}\text{Cr}$  anomalies of the CC groups (Fig. 2). Most refractory inclusions have  $\epsilon^{54}\text{Cr}$  values of  $\sim 6$  [e.g., 12] and, therefore, cannot represent the non-matrix component. By contrast, chondrules from CV and CO have an average  $\epsilon^{54}\text{Cr}$  of  $\sim 0.7$  [13,14] and represent a viable non-matrix mixing endmember (Fig. 2). Combined the correlated  $\delta^{128/126}\text{Te}$  and  $\epsilon^{54}\text{Cr}$  variations suggests that the bulk chemical and isotopic variations among the CC groups reflect mixing of CI-like,  $^{54}\text{Cr}$ -enriched and isotopically heavy matrix with isotopically light and  $^{54}\text{Cr}$ -poor chondrules.

This interpretation implies that chondrules and matrix derive from different regions of the disk, because

otherwise they would not have distinct  $\epsilon^{54}\text{Cr}$  signatures. However, the complementary chemical and isotopic compositions of chondrules and matrix imply that both components formed from a given reservoir of nebular dust [5,6]. These seemingly contradictory observations can be reconciled if chondrites, in addition to CI-like matrix, also contain 'chondrule-related matrix', where only the latter is chemically and isotopically complementary to chondrules [3,15]. Alternatively, the complementarity may primarily be hosted in chondrule rims, which later react with CI-like matrix [16]. In both case, the variable addition of CI-like matrix to a closed system of chondrules and associated chondrule-related matrix would move the bulk composition of a chondrite towards the CI composition, but would at the same time maintain chondrule-matrix complementarity [15].

**Conclusions:** Carbonaceous chondrite groups CI, CM, CV, and CO, together with the ungrouped carbonaceous chondrite TL show systematic mass-dependent Te isotope variations that correlate with Te concentration, the amount of matrix, and  $\epsilon^{54}\text{Cr}$ . These trends are best accounted for by variable mixtures of isotopically heavy CI-like matrix and isotopically light chondrules. This implies that all CCs contain some CI-like matrix, consistent with [3,4]. Nevertheless, the variable  $\delta^{128/126}\text{Te}$  among the CC groups indicate that CI-like matrix is not the sole source of volatiles, but that chondrules also contained some volatiles. The volatile fractionations among the CCs, therefore, result from chondrule formation, where the degree of depletion reflects the amount of added CI-like matrix. The correlation of  $\delta^{128/126}\text{Te}$  and  $\epsilon^{54}\text{Cr}$  suggests that chondrules and CI-like matrix formed in different regions of the disk. To reconcile this observation with chondrule-matrix complementarity requires that two kinds of matrix are present and that neither chondrules nor chondrule-related matrix have been lost prior to parent body accretion.

**References:** [1] Anders E. (1964) *Space Sci. Rev.*, 3, 583-714 [2] Larimer J. & Anders E. (1967) *GCA*, 31, 1239-1270. [3] Braukmüller N. et al. (2018) *GCA*, 239, 17-48. [4] Alexander C. (2019) *GCA*, 254, 277-309. [5] Pringle E. et al. (2017) *EPSL*, 468, 62-71. [6] Luck J.-M. et al. (2005) *GCA*, 69, 5351-5363. [7] Hezel D. & Palme H. (2010) *EPSL*, 294, 85-93. [8] Budde G. et al. (2016) *PNAS*, 113, 2886-2891. [9] Fehr M. et al. (2018) *GCA*, 222, 17-33. [10] Brennecke G. et al. (2017) *GCA*, 201, 331-344. [11] Wombacher F. et al. (2008) *GCA*, 72, 646-667. [12] Torrano Z. et al. (2017) *LPSC 48*, #3045 [13] Zhu K. et al. (2019) *ApJ*, 873, 82-90. [14] Olsen M. et al. (2016) *GCA*, 191, 118-138. [15] Jacquet E. et al. (2016) *MAPS*, 51, 851-869. [16] van Kooten E. et al. (2019) *PNAS*, 116, 18860-18866.